

# COMBINATION OF GPS PPP AND TWO-WAY TIME TRANSFER FOR TAI COMPUTATION

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## Abstract

*To follow the CCTF 2006 recommendation of using high-precision GPS carrier-phase data (CP) for TAI generation, BIPM computes monthly the GPS PPP (Precise Point Positioning) time links and publishes the result on the TAI ftp site. The GPS PPP is a combined solution of the codes and CP information. The latter assigns the high precision to the PPP result. It is shown that the PPP links have a better time stability than the TW ones in short and middle terms (up to a week). On the other hand, TW could be more stable on the long term, due to its symmetric measurement procedure and its more accurate absolute calibration. The combination of PPP and TW may benefit the advantages of both links. Because the GPS and TW are completely independent techniques, combination of them makes the results less noisy, less biased, and more robust. The combination gives also a possibility to analyze the errors presented in each technique. One of them is the diurnal deviation in some TW KU band links. In this paper, we first briefly review the recent study on the uncertainties of PPP and TW, then quickly recall the model used for the combination, and finally evaluate of the method proposed using measuring data. The TAI time network is highly redundant. This approach gives a new idea about fully using the potential of the two fundamental time transfer techniques: GPS and TW.*

## 1. INTRODUCTION

GPS PPP stands for time transfer using the Precise Point Positioning technique. Many authors studied this technique and concerned problems, such as Kouba, Héroux, Ray, Cerretto, Orgiazzi, Guyennon, Dach, Defraigne, Petit and Jiang, etc. [1-5]. PPP time transfer is now becoming operational. BIPM gathered the study results and reported to the CCTF 2006. It is recognized that the GPS carrier-phase information is a powerful tool to improve the quality of time links and to answer the new challenge of comparing new generation clocks. Following accordance with the CCTF 2006 Recommendation 4, BIPM will routinely compute the PPP time transfer and put available the results on its ftp site.

We know that the stability in the PPP solution is dominated by the accuracy and high rate of the carrier-phase information. Earlier studies have proven that the combination of TW and the scale-less GPS carrier phase can considerably improve the TW time transfer stability without changing its calibration [4,5]. In this paper, we will show that PPP may be used in the same way with similar result for time and frequency transfer.

In the TAI computation, about 20% of TAI laboratories which concentrate nearly 70% of the total weight of the TAI clocks and host all 11 PFS (Primary Frequency Standards), have both TW and PPP data. In fact, TAI time transfer network is highly redundant. Almost all the TW laboratories are backed up by the

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geodetic GPS receivers. However, the current TAI time link strategy is that we use only the primary technique, either TW or GPS, but never both.

In view of time stability, TW and PPP show their advantages in different averaging times. We show this by comparing the uncertainty types A and B ( $u_A$ ,  $u_B$ ) in TAI time transfer. First  $u_A$  represents the statistical uncertainty and is dominated by the measurement error. For short terms up to several-day averaging, the stability of PPP is obviously better than that of TW due to, as discussed below, the rather bigger noises and diurnals in TW measurements. For middle terms up to month(s), it is difficult to discriminate both techniques, but TW might be more advantageous than any GPS techniques. Secondly,  $u_B$  represents the uncertainty of the absolute calibration of the equipment. The  $u_B$  of PPP is that of the P3 code and is estimated to be of order 5 ns for a link. The  $u_B$  of TW may be as small as 1 ns. However, the TW calibration also depends on the communication satellites involved and any change in the ground equipment or in the satellite would lose the TW calibration. Obviously, each technique has its advantages and disadvantages. Combining the two techniques makes sense: a) They involve completely independent hardware and use different satellite systems; b) The combination allows one to keep the advantages, to reduce the disadvantages, and to make the result less noisy, less biased, and more robust; c) The combination gives a possibility of recovering the TW calibration at the PPP resolution of about 100 ps; that is, we can first calibrate the GPS receiver with respect to the TW and then when the TW calibration is lost, we can restore it with the GPS (this is the so-called bridge calibration), and d) It is a solution for the high redundancy in the TAI network so as to fully use the total potential of different time link data. Furthermore, we cannot evade this problem as more and more new techniques are coming, e.g., Glonass, Galileo, Compass, etc.; the question of how to combine different techniques is inevitable.

The mathematical method used is the Vondrak-Ceppek combined smoothing [7], which has been discussed in the earlier publication [4,5]. We review here only the principle of the method. The input required is of two series: S1 is the TW measurements, which are the clock differences, and S2 is the derivatives of the clock differences calculated with the rate of PPP. By this configuration of the data sets, we know, onto the output, the TW will contribute to the calibration with its uncertainty  $u_B$  and the GPS PPP will contribute mainly the improvement in the time stability with its uncertainty  $u_A$ . The combined smoothing is performed under the three conditions:  $F$ : close to S1;  $F^\circ$ : close to S2, and  $S$ : smoothness of the combined series S3, written as:

$$Q = S + \varepsilon F + \varepsilon^\circ F^\circ = \min$$

Here  $\varepsilon$  and  $\varepsilon^\circ$  are the smoothing coefficients. By adjusting them, we obtain the optimal combination result. It is an iteration procedure based on the spectral analysis of the TW and PPP data sets.

## 2. NUMERICAL TESTS

We use two tools to examine the gains obtained by the TW-PPP combination. The first is the well known Time deviation Tdev, which measures the stability, and the second is the closure analysis, which also addresses (to some level) the accuracy. We first discuss the closure analysis as an index of the time link quality and then discuss in detail how much the gains will be. Because the TW calibration is not a point in the following tests, we use all the available TW data, whether they are calibrated or not. Three triangles, all with H-maser links, are fully analyzed. They are the short and long baselines between PTB in Germany, IT in Italy, NIST and USNO in USA, and the triangle between KRIS in South Korea, TL in Chinese Taipei, and NICT in Japan. TW and GPS PPP data were gathered as a typical TAI month: TAI 0709 (Sept. 2007, MJD 54344-54369, totally 25 days).

Table 1. Statistics of the TW0709 closures.

<b>Triangles</b>	<b>:</b>	<b>Mean</b>	<b>RMS</b>	<b>StdD</b>	<b>Triangles</b>	<b>:</b>	<b>Mean</b>	<b>RMS</b>	<b>StdD</b>
CH SP USNO	:	1.00	1.01	<b>0.15</b>	PTB VSL NIST	:	0.17	0.88	<b>0.87</b>
CH USNO ROA	:	0.60	0.68	<b>0.32</b>	PTB NIST IT	:	-1.18	1.20	<b>0.20</b>
CH VSL NIST	:	0.82	1.32	<b>1.03</b>	ROA SP USNO	:	1.45	1.48	<b>0.31</b>
CH NIST IT	:	-0.38	0.41	<b>0.13</b>	ROA OP VSL	:	-1.17	1.60	<b>1.10</b>
CH IT PTB	:	-1.40	1.40	<b>0.12</b>	ROA VSL NIST	:	0.12	0.93	<b>0.92</b>
CH PTB SP	:	0.00	0.14	<b>0.14</b>	ROA NIST IT	:	-0.30	1.57	<b>1.54</b>
IT SP USNO	:	-0.15	0.23	<b>0.17</b>	ROA IT PTB	:	-0.23	0.26	<b>0.11</b>
IT USNO ROA	:	1.57	1.60	<b>0.32</b>	ROA PTB SP	:	-0.65	0.68	<b>0.19</b>
IT ROA OP	:	0.45	0.86	<b>0.73</b>	SP USNO ROA	:	1.45	1.48	<b>0.31</b>
IT OP VSL	:	-1.42	2.25	<b>1.75</b>	SP ROA OP	:	0.85	1.74	<b>1.52</b>
IT VSL NIST	:	-0.38	1.14	<b>1.07</b>	SP OP VSL	:	-1.78	2.99	<b>2.40</b>
IT PTB SP	:	-0.85	0.87	<b>0.17</b>	SP VSL NIST	:	-1.22	1.29	<b>0.43</b>
NIST ROA OP	:	-0.13	1.35	<b>1.34</b>	SP NIST IT	:	0.77	1.11	<b>0.80</b>
NIST OP VSL	:	-0.92	1.99	<b>1.77</b>	SP IT PTB	:	-0.85	0.87	<b>0.17</b>
NIST IT PTB	:	-1.18	1.20	<b>0.20</b>	VSL SP USNO	:	0.97	1.00	<b>0.25</b>
NIST PTB SP	:	1.10	1.40	<b>0.87</b>	VSL USNO ROA	:	0.72	0.79	<b>0.33</b>
OP SP USNO	:	1.65	2.30	<b>1.60</b>	VSL ROA OP	:	-1.17	1.60	<b>1.10</b>
OP USNO ROA	:	0.65	0.76	<b>0.40</b>	VSL NIST IT	:	-0.38	1.14	<b>1.07</b>
OP VSL NIST	:	-0.92	1.99	<b>1.77</b>	VSL IT PTB	:	-0.63	0.73	<b>0.37</b>
OP NIST IT	:	-0.88	0.96	<b>0.37</b>	VSL PTB SP	:	-0.28	0.34	<b>0.19</b>
OP IT PTB	:	0.42	1.59	<b>1.54</b>	USNO ROA OP	:	0.65	0.76	<b>0.40</b>
OP PTB SP	:	-1.70	2.77	<b>2.18</b>	USNO OP VSL	:	-1.10	1.65	<b>1.22</b>
PTB SP USNO	:	0.62	0.63	<b>0.13</b>	USNO IT PTB	:	-1.62	1.63	<b>0.23</b>
PTB USNO ROA	:	0.18	0.41	<b>0.36</b>	USNO PTB SP	:	0.62	0.63	<b>0.13</b>
PTB ROA OP	:	-0.20	0.85	<b>0.83</b>	NICT KRIS TL	:	-0.48	0.51	<b>0.16</b>
PTB OP VSL	:	-0.37	0.67	<b>0.56</b>					

## 2.1 THE TW LINK CLOSURE

The definition of the TW link closure is simple: a triangle closure equals the sum of the three time link vectors between the three time laboratories (Fig. 1):

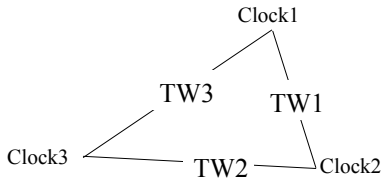


Fig. 1. Definition of a triangle closure of TW time links:

$$\begin{aligned}
 \text{Closure} &= \text{TW1} + \text{TW2} + \text{TW3} \\
 &= (\text{Clock2} - \text{Clock1}) + (\text{Clock3} - \text{Clock2}) + (\text{Clock1} - \text{Clock3}) \\
 &= V1 + V2 + V3
 \end{aligned}$$

V1, V2, and V3 are the measurement errors of the time links TW1, TW2, and TW3 measured independently. By definition, all the clocks are cancelled in the closure, if all measurements are simultaneous. Because the clocks are H-masers, any effect of nonsimultaneity is negligible and the closure should equal to zero if there were not measurement errors. A nonzero closure is a true error. The closures statistic gives us a true error index to judge the quality of the TW links. On average, there are 10-12 points per day and such about 260 triangle closures for the TAI0709. In the above equation, the terms V1, V2, and V3 can be rigorously and uniquely determined. But this is not the point of this paper. Interested people can refer to [8].

Table 1 displays the statistics of the 55 TW closures for TAI 0709. The mean values are not zero, but vary between  $\pm 2$  ns. The STD (standard deviation around the mean value) of the closures varies between  $\pm 1$  ns, except for a few cases.

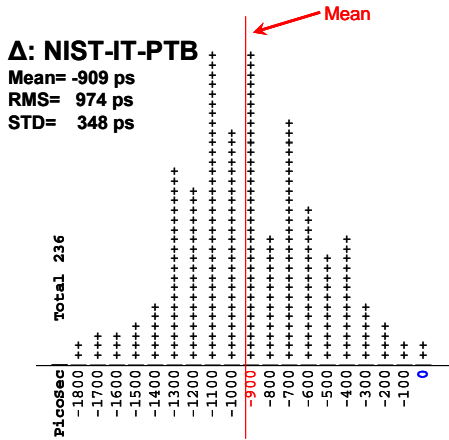


Fig. 2. Histogram of the TW closures of the TW link triangle NIST-IT-PTB. It is of the Europe-America long-distance baseline. There are 10-12 points per day and totally 236 points over the 25 days for TAI 0709, 2007 Sept.

Fig. 2 is the histogram of the TW closures for the baseline triangle NIST-IT-PTB. The mean value is -909 ps with the RMS 947 ps. The STD is 348 ps due to mainly the measurement noises and diurnal errors.

## 2.2 MEASUREMENT NOISES AND DIURNALS

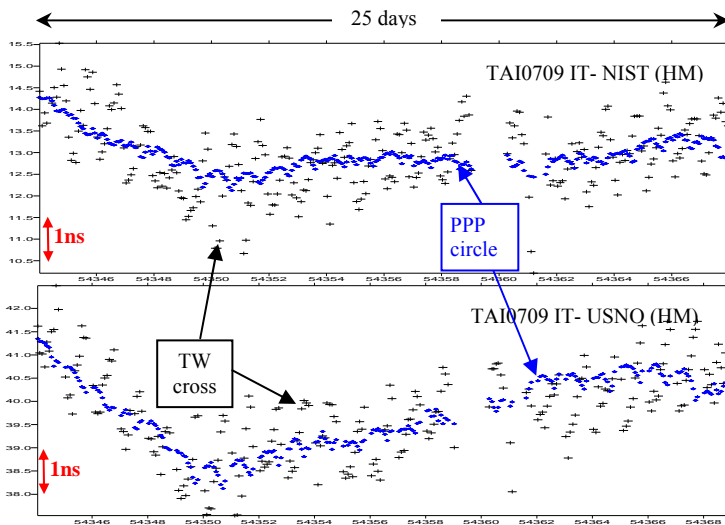


Fig. 3. Comparison of the measurement noises between the TW and PPP for the TAI 0709 links IT-NIST and IT-USNO, all with HM clocks. The peak-to-peak scatter is 2-3 ns for TW and 0.3 ns for PPP. It might not be a normal case for the TW links, cf. Fig. 4.

Fig. 3 is the comparison of the noise level between TW and PPP time links IT-NIST and IT-USNO. They are both the long-distance and H-maser links. The black points are of TW with a peak-to-peak scatters of 2-3 ns, which are obviously due to noise in this link. Tdev analysis (Fig. 4) shows the level of diurnal signals, which dominate up to averaging time of about 2 days. The blue points are of the PPP, with a scatter about several hundred ps.

Several authors have already discussed the diurnals. At present, we cannot give a reasonable explanation for the physical mechanism of the diurnals. Therefore, we have not yet a successful method to remove or reduce the diurnals in the raw TW data. What we can do is to remove or reduce them with the help of GPS PPP. The curves on the left in Fig. 4 show that strong diurnals are clearly visible throughout the whole month. Further proof can be seen in the Tdev. In the middle plots, one cannot miss the strong

diurnal signals in the Tdev. On the other hand, the plots on the right are the Tdev of the related PPP links, with only very slight diurnals that can so far be ignored.

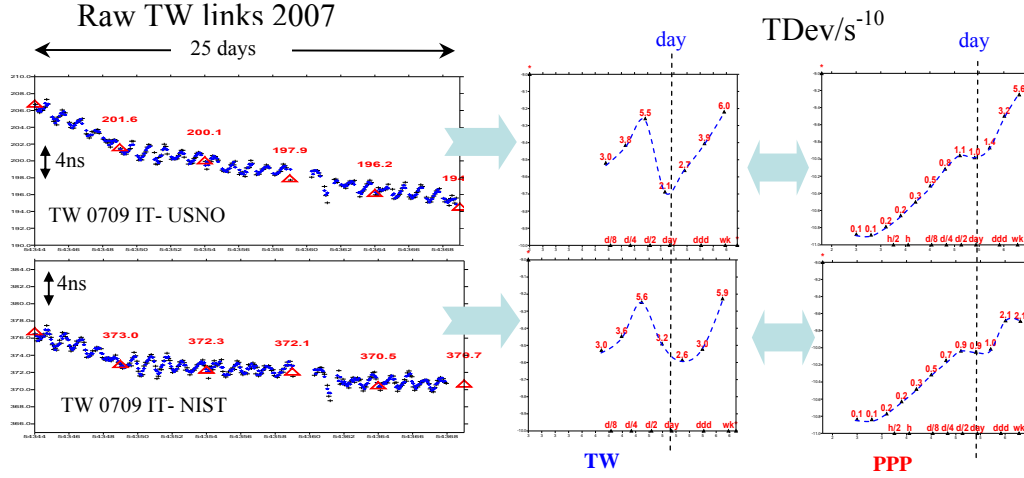


Fig. 4. The diurnals in TW time links. Left: the raw TW links where clear diurnals are visible; Middle: the Tdev corresponding to the raw TW links; Right: the raw PPP links, where no significant diurnals exist. Units are ns for the links and 0.1 ns for Tdev.

### 2.3 COMBINATION OF TW AND PPP

By the above comparisons and in view of the noise and diurnals, the PPP is more advantageous than TW. This is the physical basis of the combination of the two techniques.

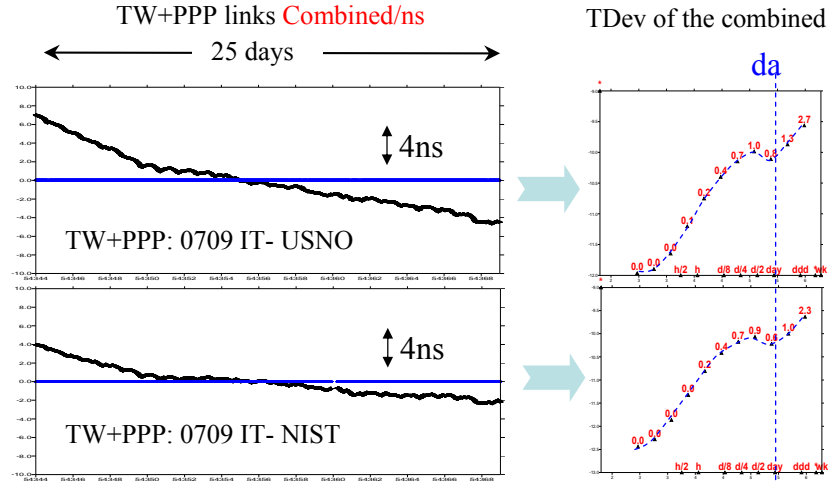


Fig. 5. Results of the combined TW+PPP links. Units are ns for the links and 0.1 ns for Tdev.

Fig. 5 is the combined time link. Compared the curves in Fig. 5 with the same TW links and the related Tdev in Fig. 4, both the noises and the diurnals are greatly reduced.

Now we look at the combination using closures as another tool. As mentioned above, the nonzero closure represents a true error. The closure analysis gives a true index of how much the improvement in the combined result. Fig. 6 presents the histograms of the closures of the three triangles. The blue histograms are of the raw TW closures and the red ones are of the closures of the combined links. The mean value and the RMS have practically no change. This implies the combination keeps the calibration defined by TW. The STD is reduced about 40% for NIST-IT-PTB and as big as 476% for USNO-IT-PTB. The Asia triangle NICT-KRIS-TL is relatively smaller. The STD of the raw data closures is already very small; only 121 ps that approximate the limit of the TW stability. But even in this case, the STD is reduced 34%. This further proves that the time stability of PPP is better than that of the best TW links. The closures, especially those with large standard deviation, are greatly reduced. Comparing Fig. 4, 5, and 6, closures are reduced partially because the diurnals become smaller.

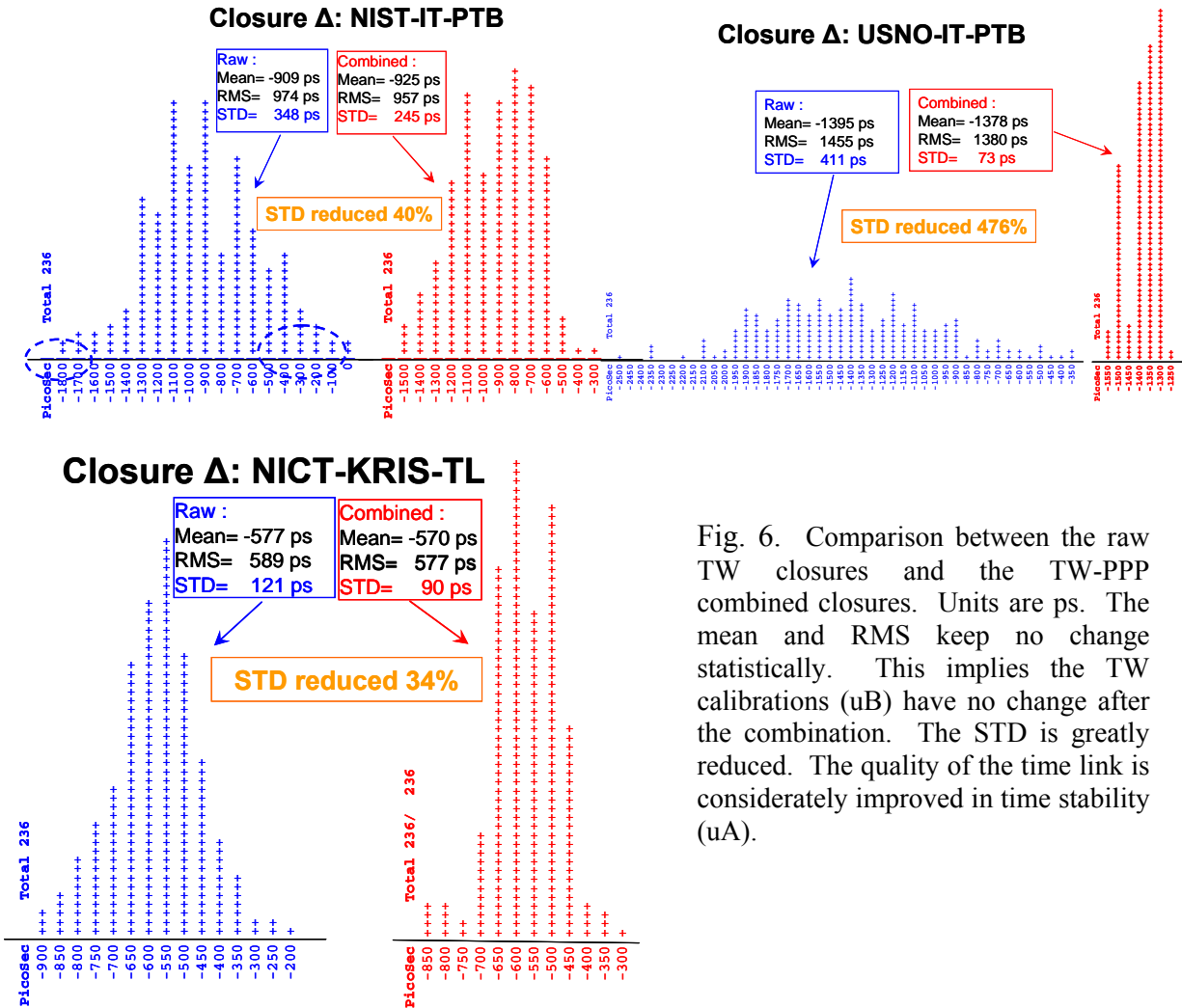


Fig. 6. Comparison between the raw TW closures and the TW-PPP combined closures. Units are ps. The mean and RMS keep no change statistically. This implies the TW calibrations (uB) have no change after the combination. The STD is greatly reduced. The quality of the time link is considerably improved in time stability (uA).

## 2.4 THE REDUNDANCY AND THE COMBINATION

Since last Oct 2006, the TAI time transfer network has become a one-pivot system; the pivot is PTB. However, there are many TW laboratories that have no direct TW link with PTB. Their TW results cannot be used for TAI. An example is the Asian lab TL. To compute the TW link TL-PTB, we have to

use the NICT as an intermediate lab to bridge the time transfer (Fig. 7). And on the other hand, all PPP links are available and their quality is independent of the distance. An application of the proposed method is to combine two TW links with a PPP link, which comprise a triangle. The comparison of the Tdev of the TW and PPP in Fig. 7 shows that there is no doubt this combination will considerably improve the quality of this Asia-Europe long-distance link. This is only an example of the redundancy of the TAI time transfer data. In fact, on many baselines, there are 300% redundant data in the TAI network. Combination of TW and PPP is a solution that fully uses the redundancy.

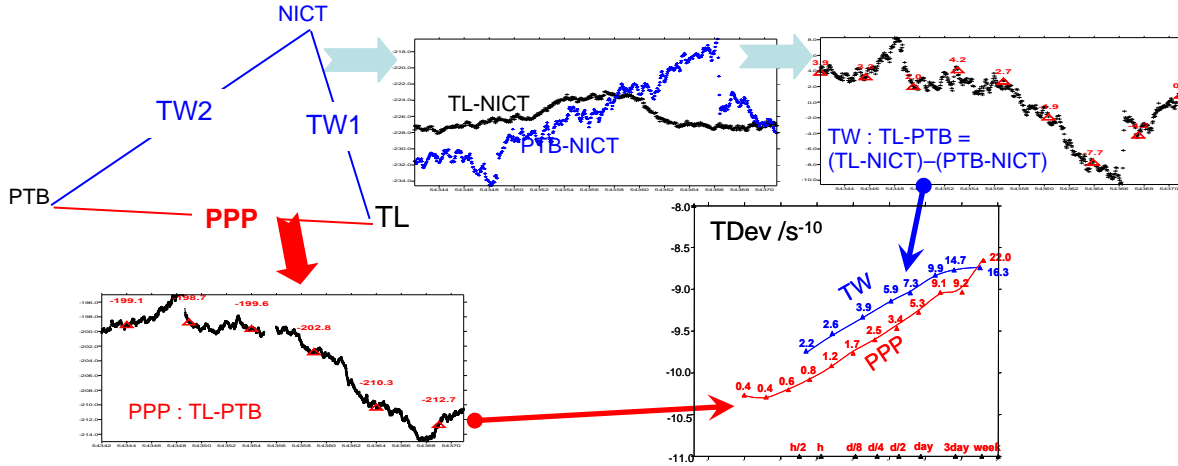


Fig. 7.  $TL-PTB = (TL-NICT) - (PTB-NICT)$ : Combining two indirect TW links and a direct PPP link. The Tdev of the PPP is well below that of the TW. The combination should greatly improve the quality of the Asia-Europe long-baseline time transfer and is a solution of high redundancy in the TAI network.

### 3. CONCLUSION

Combining two independent links TW + PPP allows: 1) full use of the advantages of the calibration and the long-term stability in TW and the short-term stability in PPP and 2) reduction of the short-term noises and the diurnals in TW as well as the poor calibration and possible biases in PPP. The combined result is of higher short- and long-term stability and more robust.

20% of TAI laboratories have both TW and PPP. They transfer 2/3 of the TAI clocks and all the 11 PFS. Combining TW+PPP of these labs will effectively improve TAI.

The proposed method allows using the high redundancy in the worldwide TAI TW-GPS time transfer network.

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